# Investigation on Vibration Characteristics of Amorphous Metal Alloy Core Dry-type Distribution Transformer

Kammeugue Noubissi Romaric, Daosheng Liu, *Member, IEEE*, and Boxue Du, *Senior Member, IEE*

***Abstract*—Large power transformers have severe vibration and noise problems. Thus, as the source of noise, it is vitally important to have accurate core vibration calculations. The calculation of the vibration is incredibly difficult to consider the complex propagation pathway of the vibration in the clamp and the Amorphous Metal Alloy Core Distribution Transformer (AMACDT). To understand the vibration characteristics of AMACDT, this manuscript provides a different approach on investigation of the vibration characteristics of an SCBH15-200/10 type. Based on the vibration characteristics calculation and displacement of an Amorphous Metal Alloy Core Distribution Transformer (AMACDT), they are obtained and solved using Finite Element Analysis software (FEA). Conferring to the outcomes of the vibration analysis, the method by adding bar-reinforcements on the upper clamp of transformer is proposed to lessen the vibration amplitude. To verify the usefulness and application of the suggested approach, the analytical results are obtained. The suggested approach is analyzed with those of experimental.**

***Index Terms*— Amorphous transformer, Finite element analysis, Vibration displacement.**

## I. INTRODUCTION

THE noise of the transformer, like the central noise supply within the station house, has accomplished increasingly public consideration. Studies described that the noise of the transformer mainly derives from electromagnetic vibration behavior as well as the core and winding vibrating [1]. The electromagnetic vibration of the core and electrodynamics force of the coil is partially assigned to reluctance magnetic forces and Lorentz, respectively [2]-[4]. The magnetostriction is a belonging of ferromagnetic instruments that provokes their sizes modification throughout the procedure of magnetization that leads to the transformer core vibration. An adequate knowledge of the noise generation mechanism of the transformer and a precise valuation of its emission properties remains important. Reference [5] has shown that magnetostriction in oriented electrical steel is the main cause of vibration and noise in electric apparatus. The valuable of magnetostriction was principally caused by the enormous range of magnetic moment. Reference [6] offered a new method for evaluating the power transformer, which analyzes the fundamental frequency elements of the vibrating signals of the core in rated settings. Transformer noise is caused by a phenomenon that causes a part of a magnetic sheet to extend itself when magnetized. Commonly stated, there are two explanations for the noise of the core: 1) magnetostrictive force of the silicon steel sheet and 2) vibration of the core [7]-[9]. Correct analysis of the entire vibration of the core is one of the main difficulties in the research of transformer's noise. The magnetic structure connection system has frequently been utilized to determine and diagnose core vibrating problems [10], [11], [12]. When the magnetization has been taken away, it goes back to its original condition.

Noise calculations of many amorphous magnetic materials such as Fe-Si-B, Ni-Fe-B and Co-Fe-Si-B, seek the adjustment to obtain the lowest noise performance. The noise of the magnetic cores is well-detailed as the oscillation of the converted voltage waveform of the magnetic cores in each cycle of the stimulating irregular magnetic field. The opened core type fluxgate magnetometer is approved as a noise testing equipment, which allows fast and simple noise analysis because winding is not required on each sample. Vibration noise was examined in relation to alloy compositions, Curie temperature, and magnetic domain patterns. The relation connecting the vibratory acceleration of the core and the magnetostriction impact was studied, and it is deduced that the acceleration or the vibratory amplitude of the core is rectilinear to the square of the voltage magnitude and the factor of magnetostriction [13], [14]. Later in [15], an operative technique to reduce acoustic radiation has been suggested by connecting a microperforated panel (MPP) in the internal part of the oil-immersed transformer. The vibration noise from different core structures was also studied in the literature [16], and the results indicate that the toroidal core design offers less vibration noise than the C-type core having rectangular and arc corners. There is no study fashionable which the fastening pressure was directly

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correlated to acoustic sound, and the ideal pressure on an amorphous metal distribution transformer still requires being further explored [17].

This work focuses to launch analytical models, analyze the vibrating of the core and transformer coils, the magnetostriction, Lorentz, and then the magnetic reticence dynamics that aided as excitation. To obtain the main excitations of the harmonic component, the Fast Fourier Transformation (FFT) is carried out on the transient strength and magnetostriction. The vibrating distributions of the transformer brackets were computed by harmonic response analysis. The structure surface distributions were then obtained to present like border settings in the sound field investigation, and the vibration distribution is found. The representational (3-D) Finite Element design for Electromagnetic Simulation (EMS), Mechanical System Analyses (Modal, structural static, Harmonic Response Analysis) are built in SolidWorks and solved in ANSYS MAXWELL that is coupled with Workbench. Conferring to the results of the analysis, the vibration reduction method was proposed by adding reinforcing bars on the upper clamp of AMACDT to suppress the magnitude at the position of maximum vibration.

## II. EXPERIMENTAL SETUP

### A. Analysis Model and Methodology

#### 1) Material Properties

The transformer bracket is made of Q235-A low carbon steel plates, the cores are in Metglas 2605SA1 low-loss amorphous alloy strip, windings are in copper, and insulation boards are in fiberglass. For modal and vibration analyses, three properties of the material need to be fixed: elastic modulus, Poisson's ratio, and density. The specific properties of the amorphous metal alloy distribution transformer material are shown in Table I. For the three-phase amorphous alloy core main magnetic field simulation, the material settings of the model in the preprocessing module are shown in table II. The modeling process is established on the coupling of dual analyses systems, the mechanical simulations and the electromagnetic as shown in Fig.1.

TABLE I
MATERIAL PROPERTIES OF AMACDT

| Components | Material Science | Density (kg/m$^3$) | Young's Modulus (Pa) | Poisson Ration |
|---|---|---|---|---|
| Brackets | Q235-A | 7850 | $2.1*10^{11}$ | 0.33 |
| Cores | 2605SA1 | 7180 | $1.1*10^{11}$ | 0.3 |
| Windings | Copper | 8300 | $1.1*10^{11}$ | 0.34 |
| Insulation | Fiber Glass | 288.33 | $5.2*10^{8}$ | 0.24 |

TABLE II
ELEMENT PROPERTIES AND MATERIALS

| Component | Material Science | Properties |
|---|---|---|
| Cores | Metglas 2605SA1 | B-H Curve |
| Windings | Copper Alloy | |
| Air | | MURX=1 |

#### 2) Core Modal Analysis of AMACDT

Modal analysis is widely practicable in the field of vibrating design to resolve the vibratory tendencies of the model or the mechanical elements, which are the normal frequency and vibrating shape of the model.

Conferring to the fundamental of modal analysis vibrating, an equation signal for core model of a transformer stands as follow:

$$M_u\ddot{u} + C_u\dot{u} + K_u u = F \tag{1}$$

Wherever $F$ represents the nodal force vector; $K_u$ represents the stiffness matrix; $M_u$ stand as the mass matrix; $C_u$ represents the damping matrix; $u$, $\dot{u}$ and $\ddot{u}$ represent the acceleration vector, the velocity and the nodal displacement respectively [18].

Analyze the natural frequency and the form of the mode, assuming that the liberated vibration of a model $F$ represents 0 and the damping constant $C_u$ is insignificant, therefore (1) might be written as follow:

$$M_u\ddot{u} + K_u u = 0 \tag{2}$$

The free vibration model is a basic harmonic vibration, so the acceleration and displacement of the vibration can be observed below:

$$\begin{cases} u = \varphi_i \sin(\omega_i + \theta_i) \\ \ddot{u} = -\omega_i^2 \varphi_i \sin(\omega_i + \theta_i) \end{cases} \tag{3}$$

Put (3) into (2):

$$(K_u - \omega_i^2 M_u)\varphi_i \sin\left(\omega_i + \theta_i\right) = 0 \tag{4}$$

The solution of the (4) is $\omega_i^2$ which is the value of the characteristic, and $i$ represents the numeral of degrees of freedom. The $\omega_i^2$ is natural spherical frequency and the normal frequency $f_i$ is:

$$f_i = \omega_i / 2\pi \tag{5}$$

The conforming characteristic vector $\varphi_i$ represents the form of the mode, which stands as the form while the model vibrates by frequency $fi$.

Fig 1. a, represents the theorical process. To determine the vibration displacements of an AMACDT, it is a great importance to firstly analyze the electromagnetic field, which aid to obtain the magnetic flux density and the forces, that serve as a data for the mechanical analysis, and the latter to determine the vibration displacement.

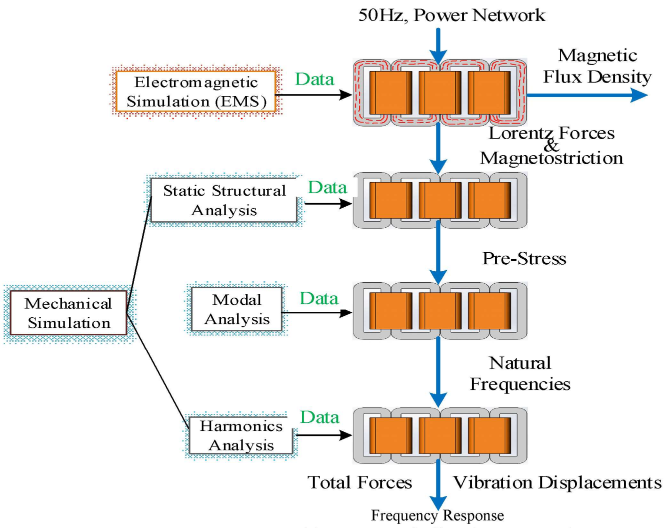
Fig 1 b, can also represent the practical process, this is done in ANSYS software by following the theorical process in order to calculate the displacement.

### B. Setup and Procedure

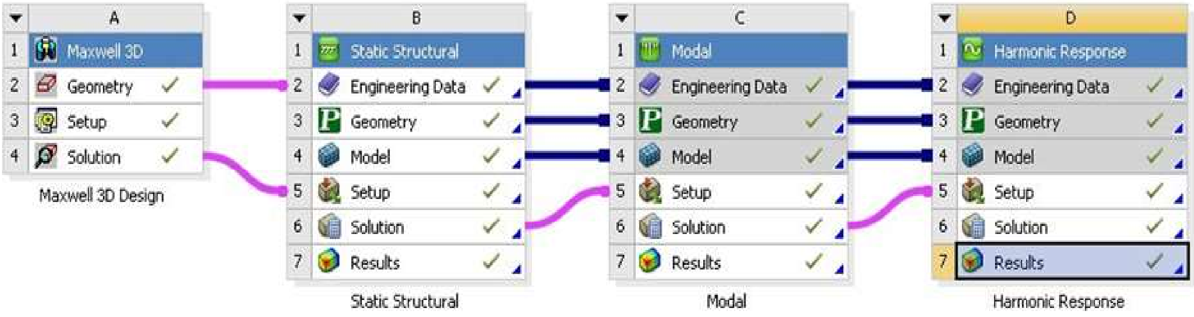
The amorphous metal alloy core distribution transformer is fabricated with especial smooth magnetic material with a size of 0.0254 mm.

The multi-channel vibrating mensuration system is represented in Fig. 2. A three-phase core of SCBH15-200/10 AMACDT is the major object of the testing in the laboratory.

The three-phase voltage controller is adapted to get an alternating current (AC) and maintain its steadiness. In Fig. 2, a supply of 400.0 V was connected to the secondary side of AMACDT with a voltage regulator when the primary side was opened-circuit. Three ICP AD1000T vibration sensors were used and placed on the upper bracket to record the vibration



(a) Process of vibration generation



(b) Workflow process in ANSYS workbench

Fig. 1. Transformer coupled simulation Process. (a) Process of vibration generation, (b) Workflow process in ANSYS Workbench.

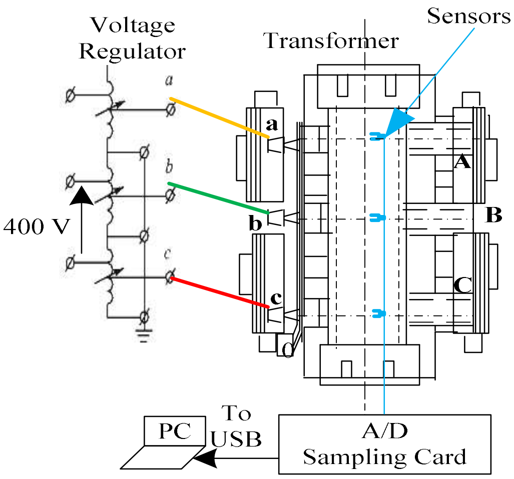


Fig. 2. Experimental platform for the measurement of vibrations at no-load condition.

signal of the AMACDT. The experimenting instrument contains three parts: vibration sensors, signal obtainment and computing unit, and vibration signal analysis. The latter consists of an A/D data sample card and a personal computer (PC).

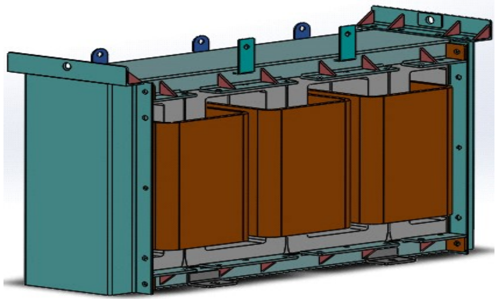
## III. SIMULATION AND ANALYSIS

### A. *Electromagnetic Simulation*

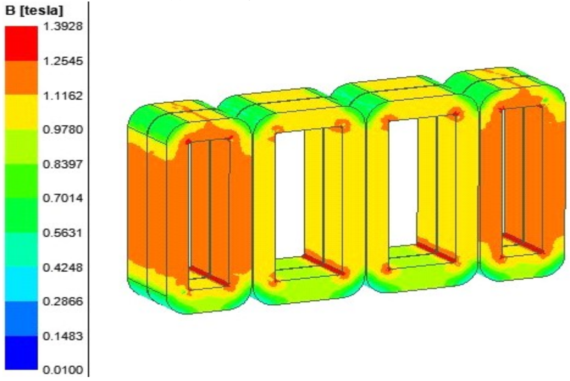
The geometry of an SCBH15-200/10 distribution transformer is shown in Fig. 3(a) and its core is composed of amorphous ribbon.

To determine the magnetic flux density of core at rated operation state that is 1.228T for Amorphous Metal Alloy core distribution transformer, a source of 400 V was connected through a voltage regulator to the secondary windings of an AMACDT where the current flows when the primary side is opened-circuit, the winding coupled with the cores, create some forces such as Lorentz forces, and the magnetostriction which is the main source of the vibration noise, the cores linked to the bracket through the insulation board, transfer the vibration energy to the bracket. Moreover, the Fig4 a, and b are the modal analysis simulation which can also indicate on how the bracket is excited. During the no-load condition, the greater the magnetic flux density is, the higher the core's vibration magnitude will be. Electromagnetic analysis of AMACDT core is represented in Fig. 3(b).

According to Fig. 3(b), maximal magnetic flux density of the three-phase core is 1.3928 T, which has evenly distributed on the four inner chamfers of the inner edge of each core. The minimum magnetic flux density is 0.01 T, which has evenly distributed at the four outer bottom chamfers of the yoke and the outer edge of the small core on the left and right sides, the magnetic flux density distribution of the outer-small core column is relatively uniform and its value is 1.2545 T. Core magnetostriction is the main factor in causing the transformer to vibrate [19], [20]. Hence, the vibration of the position where the intensity of the magnetic induction is large also increases correspondingly.



(a) Geometry of distribution transformer



(b) Three-phase core magnetic flux density distribution

Fig. 3. Electromagnetic analysis. (a) Geometry of distribution transformer, (b) Three-phase core magnetic flux density distribution.

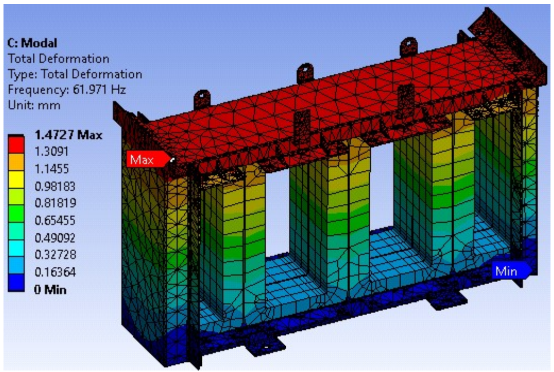
### B. *Modal Analysis Vibration of AMACDT*

However, resonance in the transformer core may be induced by increasing vibration and noise [21], [22]. Thus, resonance might appear at these harmonic frequencies. To prevent improvement of vibration caused by the phenomenon of resonance, the modification of natural frequency and excitation prevention of the core with the similar frequency while manufacturing the model of the core are necessary. As well, suitable modifications to the cross-sectional distance and the weightiness of the AMACDT core might also be favorable to reduce the vibration acoustic of the transformer [23]. The main origin of vibration is the magnetostrictive strain, so the most important frequency is 100 Hz.

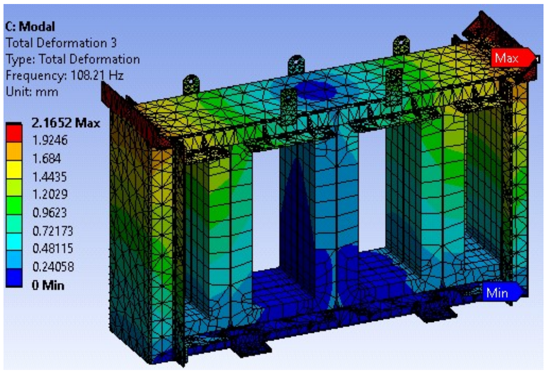
Fig. 4 presents the results of the modal analysis. The calculated natural frequencies in Fig. 4(a), and (b) show that the mode vibration at 62 Hz and 108.21 Hz are natural frequencies. The maximal deformations are 1.472, 2.165 mm respectively, and they are observed in Fig. 4(a) that at 62 Hz, the vibration trend is on the upper clamp of AMACDT that oscillates from top to bottom view. Fig. 4(b) shows the mode vibration at 108.21 Hz, and its maximum is shown on the top of the left and right-side brackets which swings relatively from side to middle of AMACDT to opposite direction.

The upper clamp is the major vibration part according to the modal analysis with a fixed support at the bottom, and the mode vibration at 62 Hz, 108.21 Hz are near to the power frequency and the multiple of the frequency respectively, and on those frequencies, the resonances present slighter damage.

The vibrating mode is higher on the upper clamp. Therefore, it is essential to investigate the vibratory characteristics on the top clamp of the AMACDT.



(a) Analysis at 62 Hz



(b) Analysis at 108.21 Hz

Fig. 4. Simulated results of the modal analysis. (a) Transformer analysis at 62 Hz, (b) Transformer analysis at 108.21 Hz.

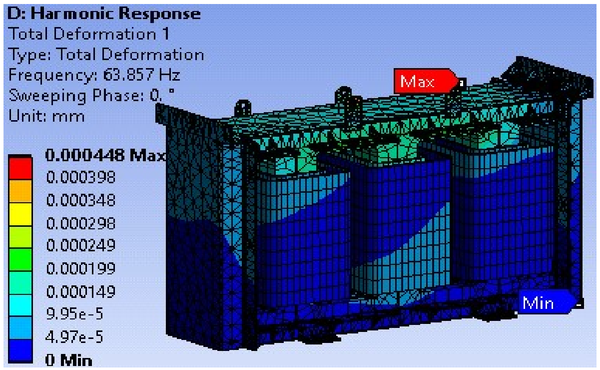
### C. *Harmonic Response Analysis*

With the outcomes of the Electromagnetic (magnetostriction, Lorentz forces), structural static, the vibration modal analysis, the mechanical displacement is gauged through harmonic response analysis. The explained and globalized equation of signal is specified in (1).

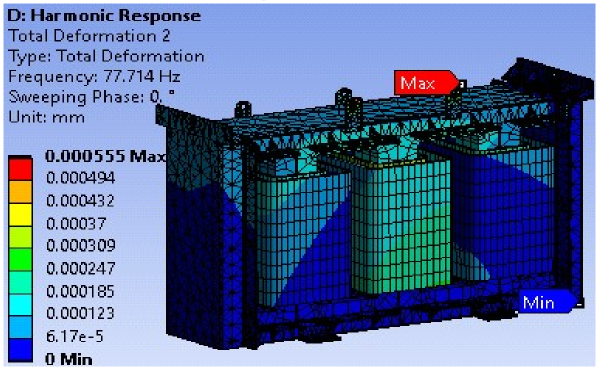
Fig. 5 shows the vibration displacements of the transformer at diverse frequencies. It is shown in Fig. 5(a), and (b) that the maximum vibration displacements are on the upper clamp of the transformer at 63.85 and 77.71 Hz, and their values are 0.00044 and 0.00055mm respectively. It also shows that the maximum vibration on the winding is 0.0003 mm on the low voltage winding at phase B.

In Fig. 5(c), the maximum displacement is on the upper clamp of the AMACDT with a value of 0.00058 mm at 91.57 Hz, and the deformation on the winding is at phase B low voltage winding with a value of 0.00032 mm. In Fig. 5(d), the maximum vibration displacement is on the left winding (phase C) with a value of 0.0024 mm at 105.43 Hz, and the maximum deformation on the top clamp of the transformer is 0.00135 mm.

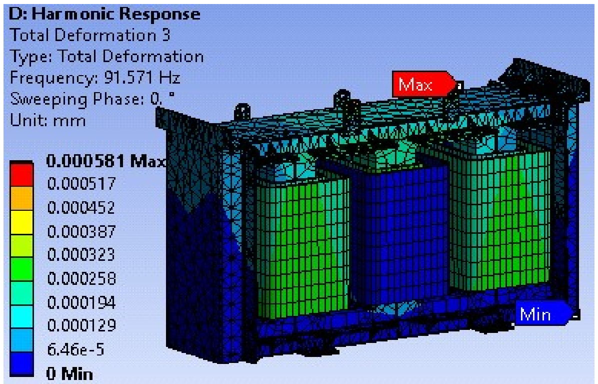
Fig. 6 shows that the vibration displacement becomes exponential after 119.29 Hz, and it increases gradually with the frequency. The vibration displacement is relational to the frequency. The higher the frequency is, the larger the vibration displacement is.



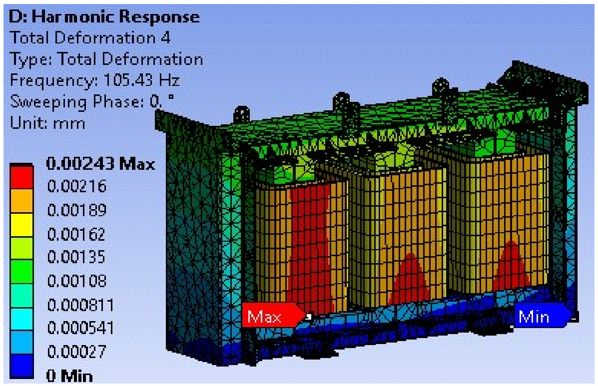
(a) Displacement at 63.857 Hz



(b) Displacement at 77.714 Hz



(c) Displacement at 91.571 Hz



(d) Displacement at 105.43 H z

Fig. 5. Vibration displacements of AMACDT by harmonic response analysis. (a) Displacement at 63.857 Hz, (b) Displacement at 77.714 Hz, (c) Displacement at 91.571 Hz, (d) Displacement at 105.43 H z.

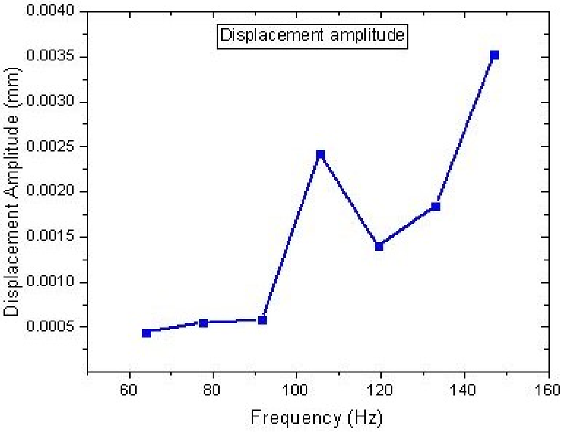


Fig. 6. Relation between the displacement and frequency of AMACDT.

The fundamental frequency of the AMACDT vibrating motion is twice the nominal frequency. The AMACDT is easily excited to resonate around 105 Hz from the harmonic response analysis, so that the vibration amplitude at 105 Hz is larger. 105 Hz represents the vibrating periodic of the AMACDT which is near to the natural frequency 100 Hz.

Analytically in ANSYS software, to extract the amplitude of the vibration displacement after a complete simulation, only the upper bracket was selected, analyzed and plot as we can observe the result in Fig 7 (b).

Fig. 7(a) and (b) present the results of the vibration displacement on the windings and on the upper clamp of the AMACDT respectively. Those representations illustrate the range of x, y, and z-element of the displacement. The results of the modal analysis have demonstrated that one of the resonance frequencies of the dynamic part and the bracket are near the double of the excitation frequency.

In Fig. 7(a) and (b), we observe that the vibration displacement is the larger at 105.43 Hz and the magnitude for the component ‘z’ is the larger one with a value of 0.0013 and 0.0011 mm, respectively.

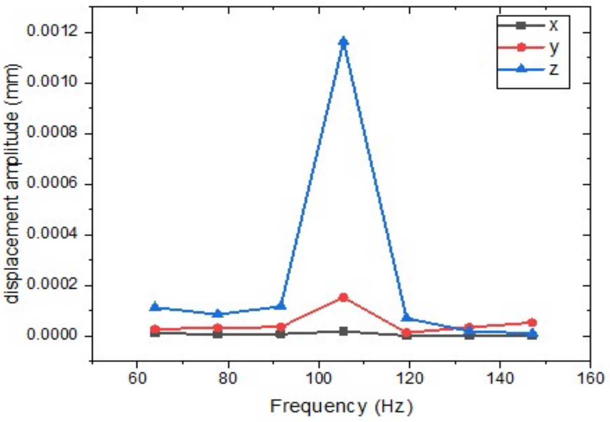
At this frequency, the vibration amplitude of the upper clamp increased then decreased. The largest vibration displacement at 105.43 Hz signifies that the AMACDT resonates under the effect of the novel approach (bar-reinforcement) which causes the higher amplitude at this frequency more obviously than other frequencies.

## IV. RESULTS AND DISCUSSIONS

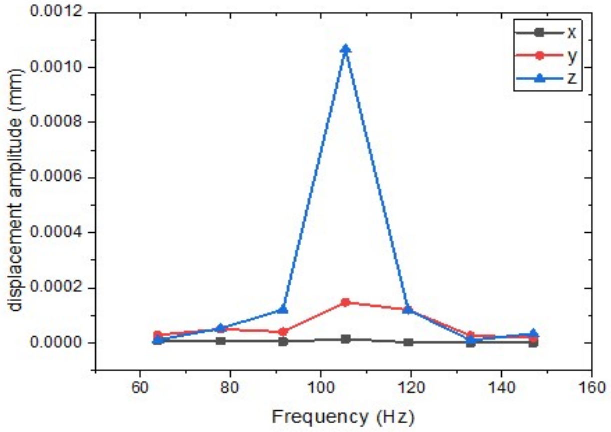
### *A. Relationship Combining Amplitude and Frequency at Diverse Phase Under No-load State*

Fig. 8 illustrates the rapport connecting the vibration amplitude and frequency in phases A, B, and C when the opened-circuit voltage was connected at the nominal rate on the AMACDT. When the applied voltages are the same, the fundamental frequency is twice higher than the power frequen cy, and its vibration periodic is 100 Hz. The magnitude of the vibration on phase B at 300 Hz is the largest one with an amplitude of 6.1151 mV. It is clarified that the high-frequency component for the vibration is produced by the forces of magnetostriction of the cores. The magnitude of the vibration of phase B impacts phases A, and C.

Moreover, the U-type support is connected to the top support of the transformer, then the vibration magnitude at phases A,



(a) displacement on the winding



(b) displacement on the upper clamp

Fig. 7. The x-, y- and z-component of the vibration displacement of AMACDT (a) displacement on the windings, (b) displacement on the upper clamp.

and C are closer to each other than phase B because of their symmetry conditions especially from 0-500Hz. Because of the magnetization of the AMACDT, the vibrations of phases A, and C are directed on the windings to the superficies of the clamp passing into the air, and the vibratory behaviors are conquered by the first-six harmonics. These studies have shown that the high-value of magnetostriction is mainly caused by the enormous transverse magnetic moment.

### B. *Effect of Bar-reinforcements Under No-load Condition*

In Fig. 8, the vibration at the upper bracket surface at phase B is higher than those of phase A, and C at 300 Hz. As the amplitude of phase B is the largest one at 300 Hz, it is deduced that the reduction of the vibrations in phase B on the upper surface of the support will reduce the vibration of the AMACDT.

The frequency-related vibration amplitude was elaborated, and from the experimental results, it illustrates that the largest magnitude position at 300 Hz is on the upper surface of the clamp at phase B. It also suggested that stimulating the vibration noise and the magneto-strictive with the electrodynamic forces have a vital role. Besides, to diminish the vibration energy, certain bar-reinforcements were attached to the upper clamp surface by the system of Fig. 9, which led to vibration noise reduction.

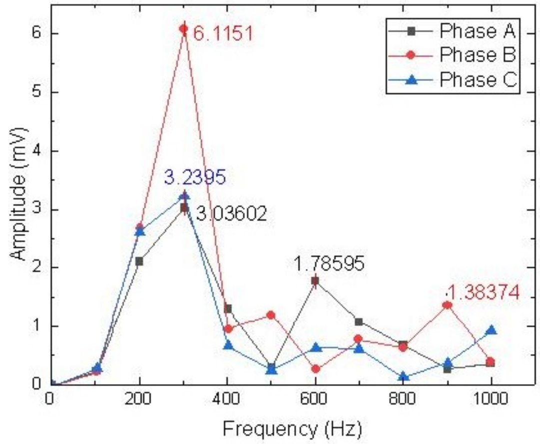


Fig. 8. Relation between amplitude-frequency at different phase.

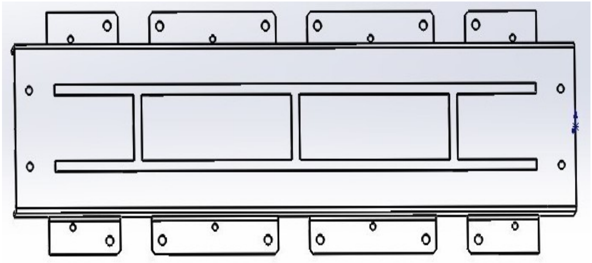


Fig. 9. Upper clamp scheme with bar-reinforcements.

Fig.10 presents the correlation connecting the amplitudes of the phases A, B, C, and the frequencies in the transformer when bar-reinforcements were added on the surface of the top support. Compared with Fig. 8, using of reinforcing bars on the upper support surface of the transformer has an effect that reduces vibration noise, and the amplitude of vibration at most frequencies has a diverse degree's drop. At 300 Hz, the values of the vibration amplitude at phase A, B, and C without bar-reinforcements are 3.03602 mV, 6.1151 mV, and 3.2395 mV and decrease to 2.3863 mV, 4.23563 mV, and 1.70289 mV, respectively, with bar-reinforcements that has reduced the vibration amplitude. After adding the bar-reinforcements on the upper bracket surface of the transformer, the energy produced by the magnetostriction decreases caused by the increasing in the distance of the spreading pathway of the vibrating wave.

As 6.1151 mV is the maximum vibration amplitude without bars-reinforcement, in Fig.10, we observed that the vibration amplitude at phase B is reduced to 4.23563 mV and represents approximately 31% of vibration reduction. Above 800 Hz, the vibration amplitude can be neglected.

However, at phase C, the rate of the vibration amplitude at 100 Hz, 500 Hz, and 800 Hz have slightly increased from 0.296 to 0.551 mV, from 0.261 to 0.7698 mV, and from 0.146 to 0.4353 mV, respectively. At Phase A, the vibration amplitude at 100 Hz and 500 Hz also lightly increased from 0.252 to 0.987 mV and from 0.3052 to 0.3232 mV, and they can be neglected.

## V. CONCLUSIONS

In this article, the vibration was analyzed for the three-phase AMACDT using ANSYS software and the Fast Fourier Transform is carried out (experimental setup) which confirmed

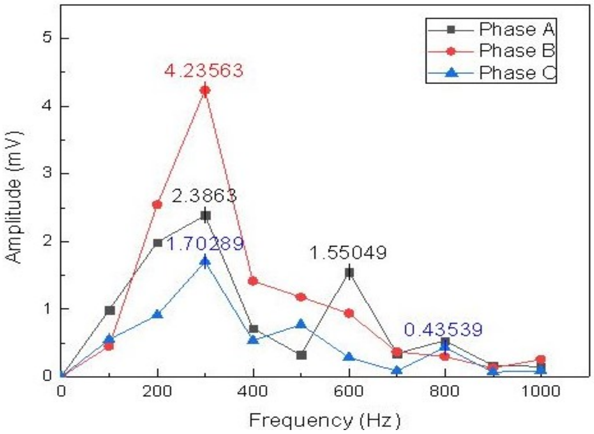


Fig. 10. Relation between amplitude-frequency at different phase with bar-reinforcements.

the practicability. From the harmonic response analysis, the vibration displacement was obtained. The calculated vibrations show that the vibrating at the top bracket of the transformer is large. Therefore, it is essential to lessen the vibration acoustic on the surface of the upper bracket for the transformer. The method to lessen the vibration at the top bracket of AMACDT cores with bar-reinforcements has been investigated, and the subsequent deduction is observed.

The fundamental frequency of the AMACDT vibrating motion is twice the nominal frequency. 100 Hz represents the vibrating periodic of the AMACDT.

The vibration amplitude of the AMACDT is the largest at phase B with a frequency of 300 Hz once the secondary is connected to the nominal voltage source, and the primary is in opened-circuit state.

The compensation of the novel approach is to lessen the vibration displacement, reducing the noise level, solidifying the static structural, reducing the stress, and deformation of transformer when occur some forces leading by a short-circuit on an AMACDT.

The results prove that the suggested approaches effectively decrease the vibration acoustic. The vibration amplitude of the transformer at phase B has 31% lower when the bar-reinforcements were added to the upper clamp of the transformer.

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